ADIT DEBRIS PROJECTION DUE TO AN EXPLOSION IN AN UNDERGROUND AMMUNITION STORAGE MAGAZINE

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ABSTRACT

The main hazards from accidental explosions in underground ammunition storage magazines are the air blast propagation and the structural debris projection exposing the terrain outside the tunnel exit. In this paper we focus on the adit debris projection part of the problem, which is not as thoroughly examined as the air blast propagation. The existing prediction methods for the adit debris quantity distance are based on a fairly small number of trials. The sparse test data available makes it difficult to establish reliable formulas for the maximum debris projection distance and the lethal debris density limit. Great care must be taken when analysing such a sparse set of data, because interpolation, and especially extrapolation, may lead to non-physical relations. In this paper we describe a method which combines theory and test data in order to extract as much knowledge as possible from the available trial results. Only the dominating physical processes are described by the model, using simple analytical formulas. Test data are used to describe the processes that can not be approximated analytically. The simulation results from a numerical code handling the required calculations are consistent with the available test data.

1 INTRODUCTION

Accidental explosions in underground ammunition storage magazines are characterised by the strong directional effect due to the adit. A large amount of the energy released in an explosion is directed through the adit, and the main hazards are the air blast propagation and the structural debris projection exposing the terrain outside the tunnel exit. In addition, breaching of the overhead cover of the magazine may occur, leading to blast venting and debris ejection, which further complicates the hazard assessments. The present study is constrained to the cases where such breaching does not occur.

The part of the problem concerning the air blast propagation is studied and fairly well understood, and the resulting prediction methods for the quantity distance are well established, although numerical predictions so far tend to overestimate the side on air blast. In this paper we focus on

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the adit debris projection part of the problem, which is not as thoroughly examined as the air blast propagation.

The existing quantity distance prediction methods for adit debris projection are based on a fairly small number of trials. The sparse test data available makes it difficult to establish reliable formulas for the debris projection distance and the lethal debris density limit. When analysing such a sparse set of data, exclusive use of interpolation and extrapolation techniques may lead to non-physical relations. Finding the correct functional relations between the various parameters involved, requires that the physics of the underlying processes is applied in the analysis. The complexity of the problem makes it difficult to establish these relations through a purely analytical approach, using the test data only to confirm the theory. In this paper we try to reproduce the available trial results by establishing a simple model that combines the use of theory and test data. If this can be achieved, the model can be used to study other initial conditions than those of the trials since the model enables a physically correct extrapolation. It has not been the intention of this study to provide a detailed mathematical description of the different physical phenomena, but rather to outline the basic ideas of the model.

2 THE MODEL

Consider a simple storage site characterised by the chamber volume V, the net explosive quantity Q and the length L_A and diameter D of the adit. Given these initial parameters, we want to establish a procedure for predicting the projection distance for *one* piece of structural debris with known mass, shape and initial location. Based on the various underlying physical processes, it is natural to divide the model into the following sub-problems:

i) The detonation in the chamber will create a blast wave followed by a flow of detonation products through the adit. A relation between the particle flow velocity in the adit, U, and the initial parameters of the problem must be found. This can be done through analytical approximations.

ii) The drag force due to the particle flow (the dynamic pressure impulse) will accelerate the piece of debris down the tunnel. A relation between the debris velocity at the tunnel exit, v'_{exit}, and the particle flow velocity, U, must be established, when assuming that no collisions with the tunnel walls occur. This relation can also be approximated analytically.

iii) The piece of debris may however collide several times with the adit walls and its velocity will consequently be reduced. The more collisions the larger reduction of the velocity, and the number of collisions increases with the distance from the initial location of the piece of debris to the tunnel exit, L, and decreases with the tunnel diameter, D. Even if the initial orientation of the debris is known, it is impossible to exactly foresee how a piece of debris is lifted by the blast wave, and what rotation and trajectory it is given, see however (1). Therefore the number of collisions is not uniquely given, but will be distributed around a mean value. A

velocity reduction factor possessing these features must be found. Assuming the factor to have an exponential form, the exit velocity can be expressed by

$$v_{exit} = v'_{exit} e^{-\beta \frac{L}{D}}, \tag{2.1}$$

as discussed in section 3.5. In equation (2.1) β is a stochastic parameter influenced by the inertia of the debris, the structure of the tunnel walls, etc. The β-distribution must be determined experimentally.

iv) The acceleration of the debris is assumed to cease at the tunnel exit, and the debris trajectory outside the adit is determined by the exit velocity and angle, and the acting air drag and gravity forces. The projection distance from the tunnel exit to the debris ground impact, R, must be found. This can be done analytically when assuming a drag coefficient.

v) The stochastic parameter β will be distributed around a mean value, hence the projection distance R will be distributed accordingly. This statistical aspect must be handled by the model.

The sub-problems i)-iv) of the model are described in detail in chapter 3.

3 IMPLEMENTATION

3.1 Particle flow velocity

The particle flow following a detonation in the chamber is primarily determined by the net explosive quantity Q and the chamber volume V. In addition the ratio of the tunnel cross section to the chamber cross section will effect the venting of the chamber. The roughness of the walls will also effect how the particle flow velocity U evolves, and generally U is given by the pressure time history in the tunnel.

A rough estimation of U can be found using a one dimensional shock tube analogy, assuming the pressure to be constant throughout the tunnel;

$$\frac{U}{c_a} = \frac{2(M^2 - 1)}{(\gamma_a + 1)M}, \tag{3.1}$$

where $M = v/c$ is the Mach number of the shock propagating down the tunnel, c_a the sound speed and γ_a the specific heat ratio in the undisturbed air in the tunnel. In this simplified analogue U is constant, giving an estimate for the velocity of the detonation products as well as for the air behind the shock. The Mach number can be found from shock tube relations (2)(3) provided that the post-detonation pressure in the chamber can be estimated. This can be done by assuming that all the chemical energy of the explosive is used to adiabatically heat up the mixture of air and detonation products to a final equilibrium. The effects of heat conduction into the surrounding rock and mechanical interaction with the surrounding rock (chamber expansion) are

neglected. When all the original mass of the explosive is assumed converted to detonation products, the equilibrium gas density in the chamber becomes

$$\rho_c = \frac{Q}{V}. \tag{3.2}$$

Here the relatively small amount of air present is neglected. When assuming that the ideal gas law applies, the equilibrium chamber pressure becomes

$$p_c = E(\gamma_c - 1)\rho_c, \tag{3.3}$$

where E is the released energy per unit mass and γ_c is the specific heat ratio. Even though the gas of detonation products is non-ideal, the use of an effective value of γ_c gives a fairly good approximation.

3.2 Debris exit velocity

The dominating force accelerating the piece of debris is the drag force due to the velocity difference, $V_r = v\text{-}U$, relative to the surrounding gas;

$$F_d(V_r) = \tfrac{1}{2}\rho A C_d(V_r) V_r^2, \tag{3.4}$$

where ρ is the gas density, A is the exposed area of the debris and $C_d(V_r)$ is the drag coefficient which is a function of V_r and debris shape. The integral of F_d represents the dynamic pressure impulse. The equation of motion is, when $V_r = v\text{-}U$:

$$m\frac{dv}{dt} = \tfrac{1}{2}\rho A C_d (v - U)^2, \tag{3.5}$$

where m is the mass of the piece of debris, v is the debris velocity. Here, the drag coefficient is supposed to be constant and equal to the initial value, $C_d(U)$. This is a good approximation because the changes in V_r, and hence in C_d, are relatively small.

By introducing

$$K_d = \tfrac{1}{2}\rho\frac{A}{m}C_d, \tag{3.6}$$

the solution of the equation becomes

$$v(t) = \frac{U^2 K_d t}{1 + U K_d t}. \tag{3.7}$$

The distance covered by the piece of debris is

$$x(t) = Ut - \frac{1}{K_d}\ln\left(1 + U K_d t\right). \tag{3.8}$$

The piece of debris reaches the tunnel exit at time $t = t_{exit}$. This time must be determined numerically from equation (3.8), and the exit velocity is then $v'_{exit} = v(t_{exit})$. The initial acceleration due to the passage of the shock front is neglected in this estimate.

3.3 Velocity reduction due to collisions

The piece of debris may collide several times with the tunnel walls and consequently lose some of its velocity. Therefore the exit velocity is generally smaller than the velocity v'_{exit} calculated above. This may be written

$$v_{exit} = K \cdot v'_{exit}, \tag{3.9}$$

where K is a factor between 0 and 1.

The actual value of K can not be predetermined even if the initial location and orientation of the piece of debris are known due to the stochastic nature of the collision process. K is roughly given by the number of collisions, which increases with the distance from the initial location of the piece of debris to the tunnel exit, L, and decreases with the tunnel diameter, D. Therefore, K is supposed to be a function of L/D, as already stated in equation (2.1). The actual form of the velocity reduction factor can be found by analysing the test data, see section 3.5. In order to do this the debris flight outside the adit must be treated.

3.4 Debris flight outside the adit

The forces acting on a flying piece of debris outside the adit are the gravity and the air drag, resulting in the following equations of motion:

$$\frac{d}{dt}\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} -\tfrac{1}{2}\rho_a \dfrac{A}{m} C_d(v) v v_x \\ -g - \tfrac{1}{2}\rho_a \dfrac{A}{m} C_d(v) v v_y \end{bmatrix}, \tag{3.10}$$

where g is the gravitational constant and x and y are the co-ordinates in the horizontal and the vertical direction. The velocity v is given as

$$v = \sqrt{v_x{}^2 + v_y{}^2}\,. \tag{3.11}$$

The initial conditions may be written

$$\begin{bmatrix} v_x(0) \\ v_y(0) \end{bmatrix} = \begin{bmatrix} v_{exit}\cos\theta_{exit} \\ v_{exit}\sin\theta_{exit} \end{bmatrix}, \tag{3.12}$$

where v_{exit} is the exit velocity and θ_{exit} is the exit angle. The exit angle will also be a stochastic variable influenced by the collision process. For convenience the exit angle is kept constant in this study.

3.5 Velocity reduction factor

The form of the velocity reduction factor K can now be found using parts of the established model to analyse the test data. In this study we use the results of the Älvdalen (4) and China Lake (5) trials. These trials are briefly described in appendix A. For each of the surveyed pieces of artificial debris in the trials, we calculate the v'_{exit} as described by the model in sections 3.1 and 3.2. The test data gives the projection distance for each piece of debris, which can be used to calculate the corresponding v_{exit} by integrating the equations of section 3.4 "backwards". For convenience the θ_{exit} is set constant to 9° during this analysis. The ratio of the two calculated exit velocities, v_{exit}/v'_{exit}, is plotted against the L/D in figure 3.1 for all the pieces of artificial debris surveyed in the tests.

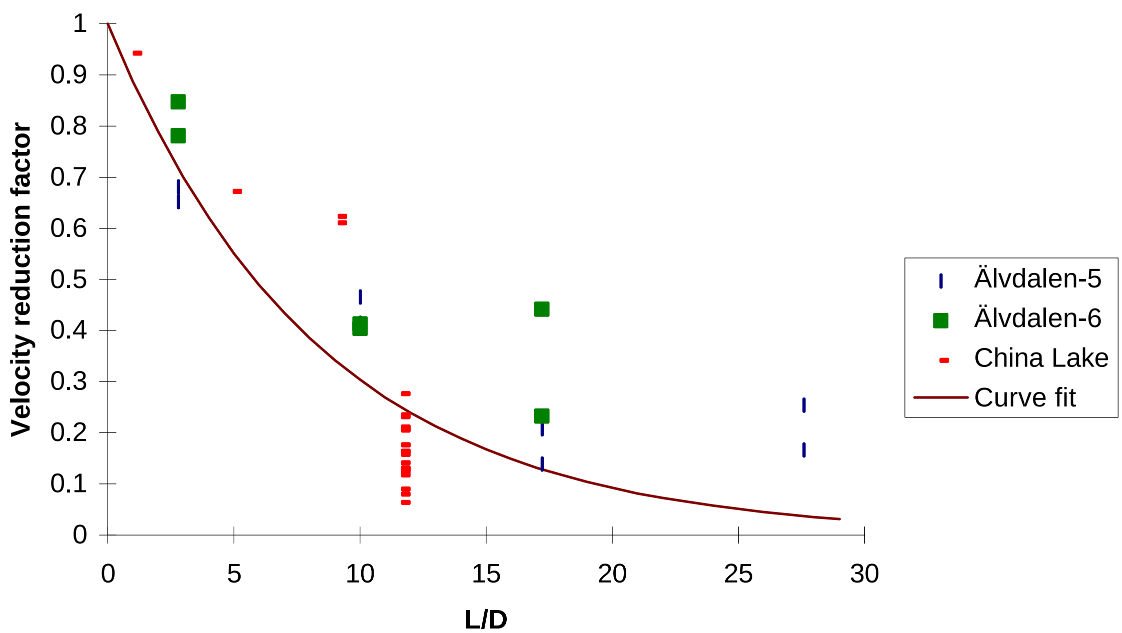

Figure 3.1: Velocity reduction factor, K*; results from the tests at Älvdalen and China Lake and a fitted exponential curve.*

The plot in figure 3.1 indicates that K should have an exponential form. The exponential form possess the correct limiting behaviour. If L equals 0, no collisions takes place and K should be 1, and if L becomes large K should approach 0. Assuming an exponential form, the velocity reduction factor can be expressed by

$$K = e^{-\beta \frac{L}{D}}, \qquad (3.13)$$

where β is a stochastic parameter.

There is a considerable scatter around the least squares fitted curve in figure 3.1, which can be interpreted as the manifestation of the stochastic nature of β. The calculated values of K can be

used to calculate the corresponding values of β, given by equation 3.13. Figure 3.2 shows the β values for the surveyed debris of the tests. The β seems to be normally distributed with mean 0.124 and standard deviation 0.050. This β-distribution can now be used to describe the collision process of any piece of debris, and the model described in i)-iv) is complete.

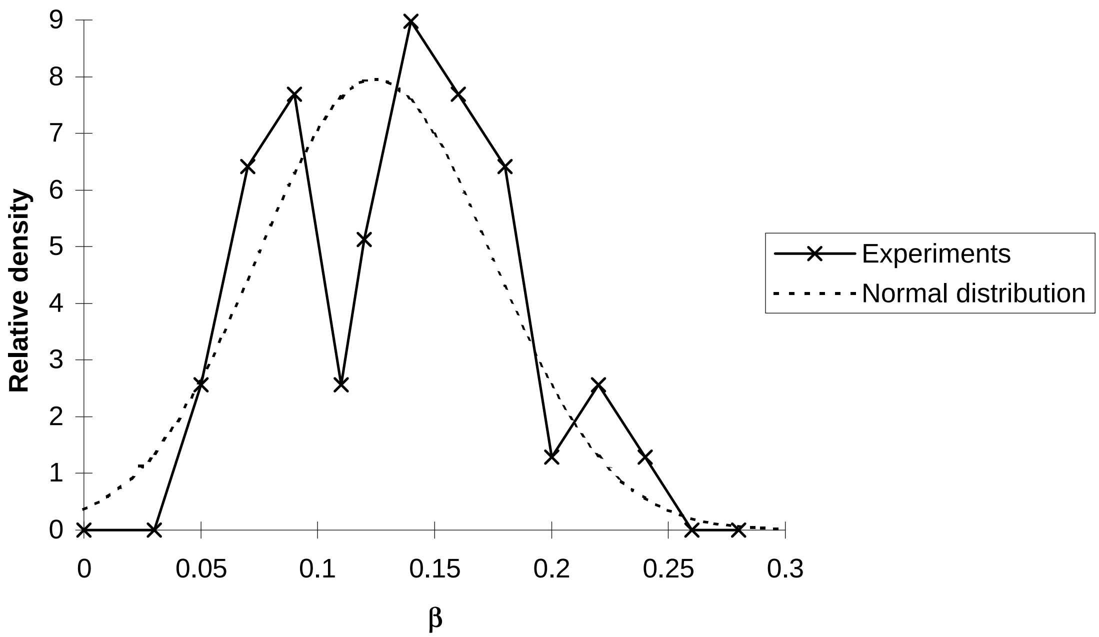

Figure 3.2: Experimental distribution of β-values and a normal distribution with mean 0.124 and standard deviation 0.050.

4 REPRODUCTION OF THE TEST DATA

4.1 Artificial debris

To test the model we try to reproduce the available test data. At China Lake (5) 36 155 mm projectiles were placed about 28 m from the tunnel exit, 21 of these were surveyed after the shot. The initial condition can be described by Q/V=100 and L/D=11.7. The columns in figure 4.1 show the distribution of the projected debris divided in range intervals of 100 m. The median of this distribution is 443 m, the 75th percentile is 664 m and the 90th percentile is 789 m. The curve in figure 4.1 shows the debris distribution produced by the model when subjected to the China Lake initial conditions. To satisfy the statistical requirements of step v) of the model, the simulation was performed with 4200 (21 200) cylinders, and the result normalised to a total of 21 cylinders. The median of the simulated distribution is 476 m, the 75th percentile 679 m and the 90th percentile 892 m. Hence the model seems to reproduce the test data well.

For other combinations of Q/V and L/D, the trials at Älvdalen (4) and China Lake (5) have only two pre-located pieces of debris for each initial condition. This makes it difficult to decide if the

simulation results are consistent with the trials. Table 4.1 shows the median, 75th and 90th percentile for the distribution of debris projection distances for the other combinations of Q/V and L/D, as well as the trial results for these combinations.

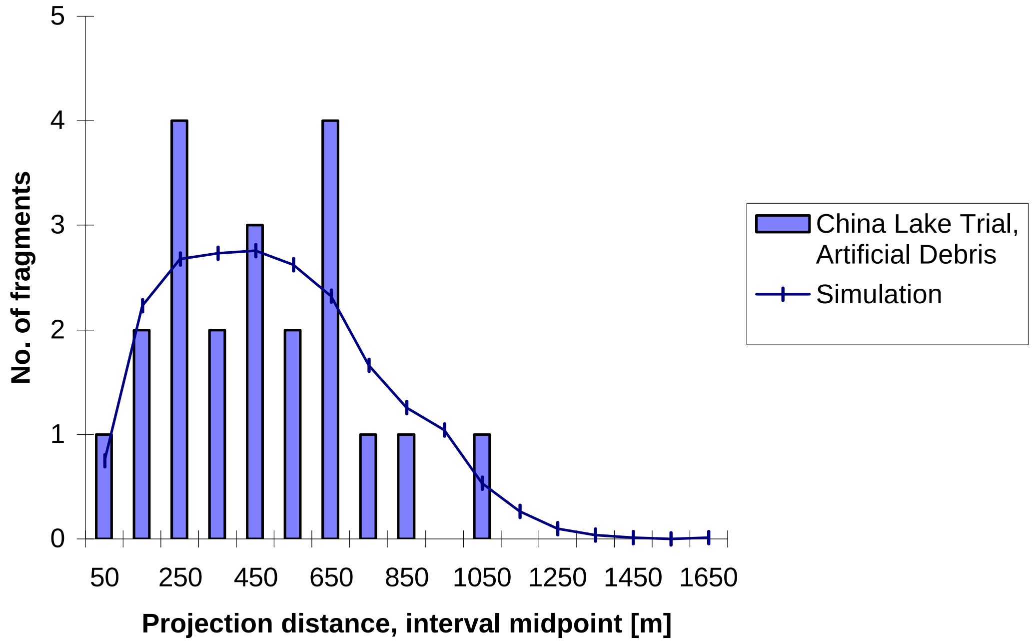

Figure 4.1: Comparison of simulation results and test data for the China Lake artificial debris survey.

Initial conditions		Simulation results			Trial results	
		Projection distance distribution [m]			Projection distance [m]	
Q/V	L/D	median	75th percentile	95th percentile		
3.33	2.8	142	164	200	240	260
3.33	10	153	249	441	235	290
3.33	17.2	57	153	481	40	90
3.33	27.6	11	63	417	80	180
5	2.8	194	221	267	330	380
5	10	193	308	510	220	230
5	17.2	83	206	568	110	370
100	1	342	358	380	1834	
100	5	592	691	818	2067	
100	9.2	563	724	980	2273	2317

Table 4.1: Comparison of simulation results and test data for various combinations for Q/V and L/D. China Lake and Älvdalen artificial debris survey.

The simulation gives consistent projection distances when the debris are initially located near the chamber. For pieces of debris initially located near the tunnel exit, the model tends to underestimate the projection distance. This indicates that the approximations made when describing the underlying processes might be too rough, and that the description should be refined. One way to explain the underestimation of the projection distances is that the acceleration of the debris do not cease at the tunnel mouth as assumed, but continue to some distance outside the exit.

4.2 Natural debris

At China Lake the naturally formed debris of rock and concrete weighing more than 10 kg were surveyed and their mass and projection distances measured. A total of 82 pieces of natural debris were surveyed and their mass distribution can be represented by a log-normal distribution with mean 5.1 and standard deviation 1.4. The model can be used to reproduce the projection distances for the natural debris at China Lake. An extra element of uncertainty is added in this simulation since the initial locations of the debris are unknown and their shapes are not well defined. In the simulation it is assumed that the debris are initially uniformly distributed in the adit, and that their masses are log-normally distributed and their shape cubic.

In figure 4.2 the columns show the distribution of the projection distances for the 82 surveyed pieces of natural debris. The median of this distribution is 473 m, the 75th percentile 711 m and the 90th percentile 770 m.

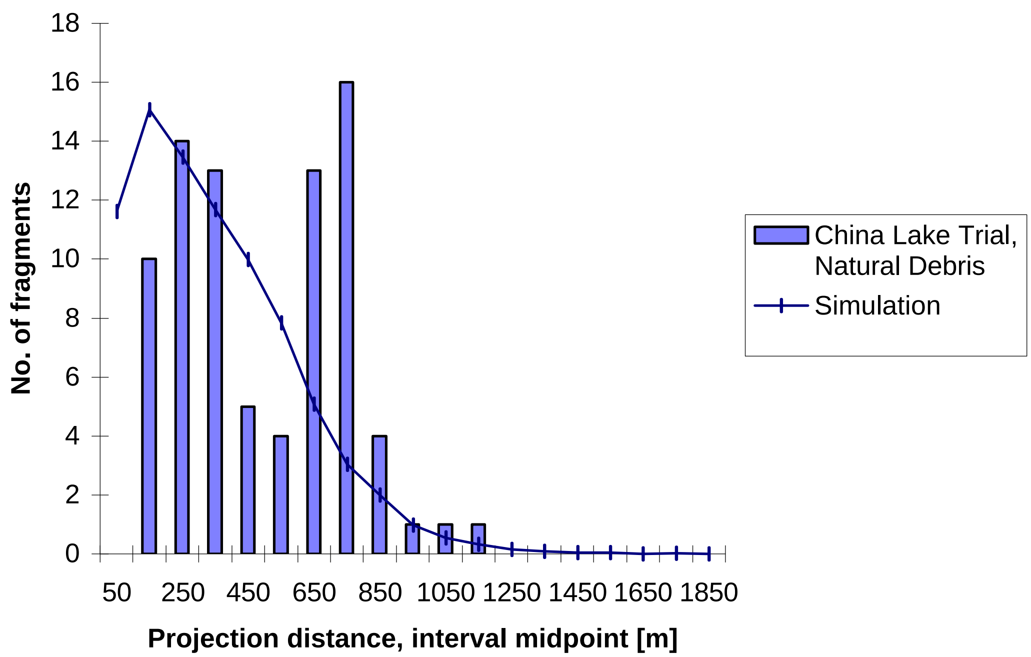

Figure 4.2: Comparison of simulation results and test data for the China Lake natural debris survey.

The curve in figure 4.2 shows the simulation results for the projection of 16400 (82 200) pieces of natural debris using the China Lake initial conditions, normalised to a total of 82 pieces of debris. The calculated distribution has a median of 307 m and a 75th percentile of 496 m and a 90th percentile of 677 m. For the projection of the natural debris the model tends to underestimate the projection distances. This might be due to an incorrect assumption of uniform initial location of the debris, or the velocity reduction factor established for cylindrical debris might overestimate the velocity reduction for cube-like debris. Considered the rough assumptions made in the simulation, the test data are reproduced to an unexpected high degree.

5 CONCLUSIONS

The simulation results produced by the model seems to be consistent with the test results. This indicates that the established model represents a mainly correct description of the physical phenomena of the problem. This also indicates that the steps i)-iv) of the model represents a correct division of the problem. The main parameters determining the projection distance can be identified to be Q/V, L/D and the distributions of mass, location and shape of the expected debris.

The model is recommended used to predict debris projection distances and to determine quantity distance prediction methods for actual storage magazines.

6 RECOMMENDATIONS FOR FURTHER WORK

The description of the physical processes of i)-iv) should however be refined, to achieve an even better reproduction of the trial results. When refining the model, it is important to maintain a balanced degree of refinement between the various processes described. In our model several short cuts have been made which should be reconsidered when improving the model:

- The particle flow velocity in the adit (or dynamic pressure impulse) should be determined based on a better representation of the pressure time history in the adit. The effect of the choking of the flow and the shock attenuation due to wall roughness should be considered.
- The ratio of the tunnel cross section to the chamber cross section will effect the amount of time needed to vent the chamber. The dynamic pressure impulse depends on this venting time and on the total amount of energy available, which indicates that Q as a representation of the available energy should be a separate parameter of the problem.
- The acceleration of the debris do not cease at the tunnel mouth as assumed, but continues to some distance outside the exit.
- The debris exit angle is kept constant in the model even though this parameter clearly is distributed. This simplification should be reconsidered.
- When analysing the test results, the measured projection distance is taken to be the distance to the first ground impact for the debris. This is probably not correct due to ricochets before the debris finally stops.

- The β-distribution in this study is entirely based on cylindrical debris. The experimental basis leading to the β-distribution should be extended, and the effect of various debris shapes studied. Survey of pre-located natural rock debris should be included in future tests, to ensure that the β-distribution represents a correct description of their collision process.

Before the model can be used to establish the quantity distance prediction methods, some additional problems must be addressed:

- The angular distribution of the debris must be described. According to the test data a normal distribution seems to be a good representation of the angular distribution.
- The initial mass distribution of potential debris for typical storage magazines must be determined by inspection.
- The effect of various safety measures in actual storage magazines must be estimated. These measures might be the geometry of the tunnels, constrictions, expansion chambers, debris traps, blast doors etc.
- The effect of the topography of the exposed terrain should also be taken into account when determining the quantity distance prediction methods.

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APPENDIX

A DESCRIPTION OF THE TRIALS

Very few full-scale experiments include survey of adit debris. Two tests including measurements of adit projection distances are the Älvdalen trials (4) in Sweden and the China Lake trials (5) in USA.

At the 1986 Älvdalen test series, the installation consisted of a tunnel with two chambers as figure A.1 shows. The volume of chamber A and B was 300 m^3 and 200 m^3 respectively. The cross section of the tunnels was 6.3 m^2. For test shots 5 and 6 at Älvdalen, there exist data for the individual positions of the placed artificial debris before and after the shots. In these tests, the charge consisted of totally 1000 kg TNT, placed in the middle of the chambers. In test 5 the charge was in chamber A and in test 6 in chamber B.

The artificial debris were steel pipes filled with concrete, and their mass was 47 kg, the length 68 cm and the diameter 16 cm. Pairs of cylinders were placed on the tunnel floor on three (test 5) or four (test 6) locations as figure A.1 shows. All the pipes were marked to make it possible to identify them after the shots.

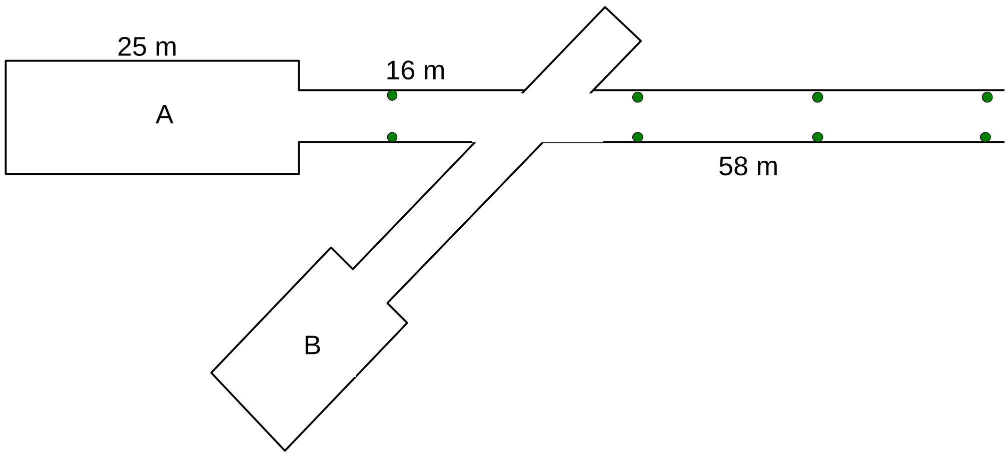

Figure A.1: Tunnel and chambers at Älvdalen.

The installation of the 1988 China Lake trial, consisted of a chamber and a tunnel as shown in figure A.2. The chamber had a 12 m^2 cross section and a volume of 220 m^3, while the cross section of the tunnel was 5.6 m^2. The charge was equivalent to 22 000 kg TNT and positioned in the centre of the chamber.

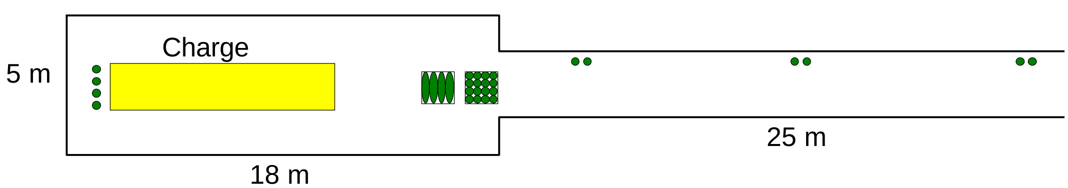

Figure A.2: Tunnel and chamber at China Lake.

As in the Älvdalen tests, pieces of artificial debris were placed in the tunnel and in the chamber, see figure A.2. The debris were sand-filled 155 mm projectiles with mass 43 kg and length 90 cm. Initially 42 projectiles were placed in the installation, 25 of these were surveyed, and their projection distances measured.